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# FUEL-AIR INJECTION EFFECTS ON COMBUSTION IN CAVITY-BASED FLAMEHOLDERS IN A SUPERSONIC FLOW (POSTPRINT)

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# Fuel-Air Injection Effects On Combustion In Cavity-Based Flameholders In a Supersonic Flow

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**The effect of fuel and air injection was experimentally studied in a cavity based flameholder in a supersonic flow. Cavity based fuel injection and flameholding offer an obstruction-free flow path in hydrocarbon fueled supersonic combustion ramjet (scramjet) engines. The characterization of cavity-based fueling systems is still largely unavailable. Therefore, the subject of this investigation was to expand the cavity based fueling system such that both fuel and air are directly injected. Additionally, this study included characterization of the operational limits (i.e., sustained combustion limits) over a variety of fuel and air flow rates. The cavity is recessed below the surface with a 90-degree rearward-facing step and a trailing ramp with a 22.5 degree ramp angle. The cavity rearward ramp includes ten span-wise injection ports at each of three axial stations configured to inject air, fuel and air respectively. Planar Laser-Induced Fluorescence (PLIF) techniques were utilized to collect planar distributions of the OH radical at various axial locations within the cavity under different flow conditions. Furthermore a high speed emissions camera was used to evaluate the combustion across the cavity. Direct injection of both fuel and air provided additional capability to tune the cavity such that a more stable decentralized flame results. The addition of air injection provided the most improvement over the baseline case (fuel only) near the upstream portion of the cavity close to the cavity step.**

## Nomenclature

| | | |
|---|---|---|
| D | = | Cavity Depth |
| FS | = | Full Scale |
| L | = | Cavity Length ($\theta=90°$) |
| OR | = | Offset Ratio ($D_u/D_d$) |
| PLIF | = | Planar Laser Induced Fluorescence |
| SLPM | = | Standard Liters Per Minute |
| x | = | Streamwise Position |
| y | = | Transverse Position |
| z | = | Spanwise Position |
| $\theta$ | = | Aft Ramp Angle |
| $\tau$ | = | Residence Time |

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# I. Introduction

Hypersonic flight has offered and will continue to offer significant payoffs for both the military and civilian populace. Flight at higher Mach numbers is conducive to business in the global market place as both high priority packages and people can be transported across great distances in short time. Military leaders can utilize this technology in the war on terror which fundamentally requires a quick response to neutralize single significant threats within narrow time windows in order to capitalize on intelligence. Higher flight velocities enable greater distances to be covered within acceptable response times. Given that today's military continues to struggle with downsizing and base closure and realignment, hypersonic vehicles offer the potential to ramp down overseas operations without a detrimental effect on response time to overseas targets. Furthermore, the high kinetic energy could also be applied to weapon systems where targets are neutralized using the kinetic energy of the warhead rather than chemical or nuclear energy. The application of SCRAMJET technology could also reduce the cost of space access by providing space vehicles with a fraction of the required escape velocity. For these reasons, SCRAMJET technology is the subject of research around the globe.[1,2]

## A. Background

Flight in the hypersonic regime has become more common since a German V2 rocket exceeded Mach 5 in 1949. Several countries now have rocket programs that provide access to space and these vehicles encounter hypersonic environments. Traditionally, however, rocket propulsion has been applied to realize hypersonic flight. Such systems, from a historical standpoint, require more fuel and oxidizer to satisfy a desire to fly farther or faster. One of the primary disadvantages of rocket propulsion at least for atmospheric hypersonic flight is that they must carry all of their oxidizer on board. This in addition to the increased number of components required to store and transport the oxidizer to the combustion chamber contributes significantly to the overall weight and complexity of the vehicle. The increased weight translates simply into larger vehicles or decreased payloads. Supersonic combustion RAMJET (SCRAMJET) engines would negate the need to carry oxidizer on board of the aircraft as all of the oxygen needed for combustion would be garnered from the atmosphere. Another advantage SCRAMJET engines have over rockets is their ability to be throttled. Thrust levels for solid rockets are based solely upon design and current liquid rockets have limited throttleability.

Supersonic combustion is inherently a difficult event. Generally speaking, combustion is an exothermic chemical process which requires fuel, oxidizer, initiation energy and time for the chemical reaction to take place. The last key ingredient is not easy to come by given supersonic flow through the SCRAMJET. The simple relationship between time distance and velocity would tend to suggest increasing the length of the engine to allow a greater time for combustion to take place given the velocity of the flow through the engine. However this would increase the weight of the engine thereby decreasing an aircraft's payload. Furthermore, it has been noted that the thrust to drag ratio of an engine is approximately proportional to the ratio of the combustor's diameter to its length.[3] This provides additional incentive to keep the combustor length to a minimum. A significant challenge in the generation of SCRAMJET propulsion is completing the combustion process within the engine. Combustion requires that fuel is introduced, mixed with the oxidizer in a sufficient quantity and then provided with energy to start the reaction process. As noted previously, this requires a finite amount of time which, given core velocity through the burner, can be related to distance. Since large distances are not feasible several techniques have been employed both computationally and experimentally to assist the combustion process. First, obstructions and/or fuel injection schemes can be introduced into the supersonic flow causing disruption in the boundary layer and the formation of shockwaves. Previous work has shown this creates a region of high turbulence that can be compared to a region of effective mixing at least on a qualitative basis. Secondly, a cavity can be introduced to the flow creating a subsonic flow region thereby increasing the residence time and creating a region of heated gases to aid in the combustion process.

## B. Previous Research

Cavity based fuel injection and flameholding offer an obstruction-free flow path in hydrocarbon fueled SCRAMJET engines. Such flame holding cavities can provide the benefit of relatively long residence times and, coupled with a direct cavity fuel injection scheme, can provide robust flame holding with minimal drag penalties in the presence of significant changes in the freestream flow field. However, detailed information regarding the behavior of these devices namely their optimal shape and fueling strategies, combustion stability and interactions with disturbances in the main air flow is largely unavailable in the existing literature.[4] Previous studies have concluded that variations in geometry affect different aspects of the flow in and around the cavity. Key geometries that affect cavity flowfields and therefore its suitability as a flameholder are as follows: length to depth ratio, offset

ratio and aft ramp angle. The length to depth ratio categorizes cavities as either open or closed. The shear layer of an open cavity spans the entire cavity length whereas the shear layer attaches to the bottom wall of a closed cavity due to the cavity's increased length. Typically, L/D<10 defines an open cavity while L/D>10 is considered a closed cavity. Studies have shown that open cavities impose a smaller drag penalty on a supersonic engine.[4] Previous low speed combustion studies found optimum flameholding performance coincided with a cavity with its length to depth ratio sized for the minimum aerodynamic drag. Longer cavities produced vortex shedding that resulted in cavity oscillations and unstable flames and shorter cavities lacked sufficient air entrainment to sustain combustion.[5] As noted before, if the cavity length increased such that the cavity was closed (L/D>10) an even greater increase in drag would occur. Cold flow calculations performed by Baurle and Gruber for various geometries show that cavity length determines mass entrainment and cavity depth determines residence time.[6,7] Changes to the offset ratio also cause drastic changes to the flowfield. As offset ratio is increased above unity a strong expansion fan takes the place of a compression wave at the forward cavity wall. Additionally, increasing the offset ratio seems to influence the vortex structure within the cavity. During a non reactive flow study performed by Gruber et al., curved waves were shown emanating from the cavity's forward wall at an offset ratio of one. These waves may be the product of the oscillatory nature of the cavity vortex. However, when the offset ratio was increased to two for the same aft ramp angle curved waves were not generated. The aft ramp angle is another key parameter affecting cavity flowfields. Gruber et al. studied the flowfield in and around several different geometric configurations under Mach 3 flow conditions. The study was non-reactive and included both schlieren and shadowgraph photography. Furthermore, a computational fluid dynamics (CFD) routine was executed for various cavity geometries. Residence time ($\tau$) was reduced from CFD data. Starting from a steady state solution the fluid is marked and the simulation is stepped forward in time while the marked fluid is monitored as it exits the cavity. The drag coefficient presented in their study is the drag force normalized by the freestream dynamic pressure and the cavity fore wall area[6]. As the aft wall angle ($\theta$) is reduced from 90° a more stable, two-dimensional flowfield is formed. The separation wave at the forward cavity step changes from compressive to expansive as $\theta$ decreases from 90˚ to 30˚ to 16˚. Additionally, reductions in the aft ramp angle from 90-30-16° resulted in higher drag coefficients and lower residence times, both of which could be considered detrimental to an effective flameholder. However, the resulting stable flowfield from a decreased aft ramp angle could justify a decrease in residence time and an increase in drag coefficient. "In general, decreasing the aft wall angle should promote both a more acoustically stable cavity flow (and subsequent stable burning) and improved entrainment because the shear layer impinges deeper into the cavity."[6] This trend has been verified in reactive studies. After several injection sites were studied for a fixed cavity geometry, a wider range of sustained flames was established using cavity ramp injection.[4]

Numerous studies have been accomplished regarding flow over open cavities as it is an often-seen configuration. There are several flow trends that should be noted. First, rectangular cavities are usually characterized by a level of unsteadiness. This unsteadiness is observed as oscillations in pressure, density and velocity in and around the cavity. Unsteadiness introduces another complicating element into the cavity flow dynamics and it has been noted that cavity flow can be very three dimensional, especially off centerline. Secondly, the creation of a lobed recirculation zone is commonly noted. Figure 1 shows the pressure contours and stream traces derived from a standard two-dimensional eddy-viscosity-based CFD turbulence model. Notice that two counter rotating lobes are formed for each of the geometries used in the simulation. Decreasing the aft ramp angle appears to decrease the size of the secondary lobe. However, for both L/D and each aft ramp angle studied a primary and secondary vortex was generated. It has been noted in previous subsonic combustor simulations that the sizes of the vortices alternate in time. Cavity flow is further complicated by the three dimensionality of the flow. The simulation results shown in Figure 1 are based on the cavity centerline where the flow tends to be two dimensional in the x-y (streamwise-transverse) plane. However, because flow is three dimensional additional structures most likely exist in the x-z (streamwise-spanwise) plane. This aerodynamic feature of cavities presents both challenges and benefits to its use as a cavity based flameholder. The region of recirculation will provide additional residence time



Figure 1 – Stream Traces
(Ref 5 Mach 3)

for combustion to take place. However the dual vortex structure may require more complicated fueling schemes to provide a uniform combustible mixture throughout the cavity.[6]
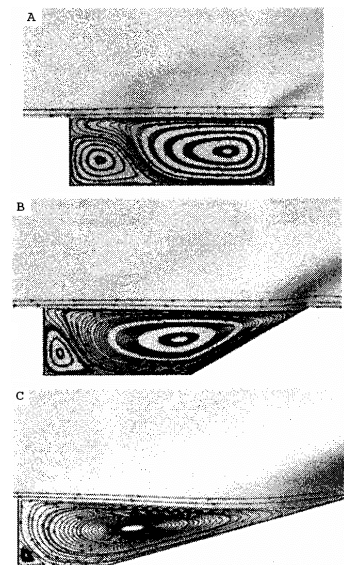
Fueling strategies must be derived to ensure a robust flameholder for both the subsonic and supersonic modes. First, consider the air entrainment rate for both the subsonic (high backpressure) and supersonic (low backpressure) cases. Figure 2 shows a representative shadowgraph images for each case. Notice the shear layer reattachment is on the aft ramp face for the purely supersonic case (low backpressure) and that it is separated from the cavity in the subsonic/supersonic case (high backpressure). This difference
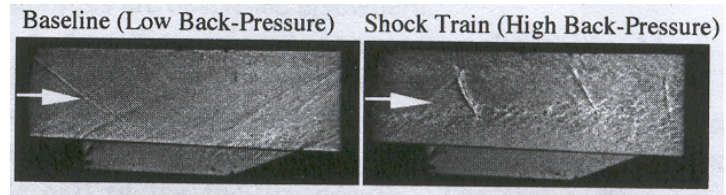


Figure 2 – Cavity Flow Conditions (Ref 4)

substantially alters the freestream entrainment which could be a mixture of fuel and air, and effectively increases the volume of the cavity in the high backpressure case. It has also been shown that mixing is enhanced within the cavity by the shock train developed at a high backpressure. A flameholding cavity was designed, fabricated and tested by the Air Force Research Laboratory at Wright-Patterson Air Force Base in Ohio through the Propulsion Sciences Branch (AFRL/PRAS). The design is shown in figure 3. The cavity has a length of 2.60 in, a depth of 0.65 inches and an aft ramp angle of 22.5°. It is an open cavity given its L/D of 4.7 and it has an offset ratio of unity. Several fuel injection strategies were studied by Gruber et al.[4] for both the high and low backpressure cases. Mixing studies involving indirect injection showed higher jet penetration given the high backpressure condition. This equated to a reduced entrainment into the cavity. They also showed that entrainment into the cavity relies largely on diffusion

through the shear layer and the interaction between the shear layer and the aft ramp face. Direct injection through F4 and F5 ports were in general better cavity fueling schemes. However, cavity fueling was still dependent on the shear layer interaction with the aft ramp. As noted before the flameholder must be effective during dual-mode operation. Several cavity combustion tests were conducted during the transition from low to



Figure 3 – Cavity Geometry

high backpressure. The only fueling scheme that produced sustained cavity combustion with the presence of the shock system was F5 (aft ramp injection). The influence of the shock system and shear layer on cavity fueling is minimized by fuel injection from F5. Despite the increased robustness of the flameholder using aft ramp injection fueling schemes, Gruber et al. noticed that some fuel injection pressures resulted in localized combustion regions. This suggested that the cavity may be too large for efficient mixing and combustion for the conditions tested. A drag penalty is paid for the inclusion of a cavity based flameholder. From this standpoint, it is important to ensure that the cavity size is kept to a minimum and therefore efficient use of cavity volume is essential. The combustion study accomplished by Gruber utilized Planar PLIF configured to detect the presence of the hydroxyl radical. For given freestream conditions, image intensity was greatest for a single fuel flow rate. This indicates that given a fuel-only flow the fuel flow rate must be tuned to obtain maximum utilization of the cavity volume with minimum flame oscillations. Aft ramp fueling strategies appear to offer the best fuel/air distribution within the cavity as well as a wide rage of fuel flow rates over which combustion may be sustained when compared to the other fueling locations studied. The fuel flow rate can be optimized and deviations from this optimal point lead to a flame with increased oscillations and large spatial gradients.[4] Fueling the entire cavity from a single streamwise location can be complicated due to the aerodynamics of the cavity vortices. Fuel must be transported from the injection site forward to the cavity step by means of these structures.
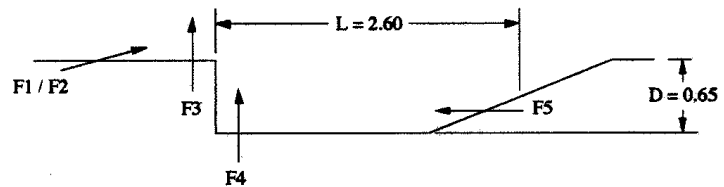
## C. Current Study

The subject of this investigation was to expand the cavity based fueling system such that both fuel and air are directly injected. It was proposed that this method would provide a uniform fuel air distribution within the cavity over a wide range of fuel flow rates and freestream conditions thereby resulting in an efficient, robust flameholder. Additionally, this study included characterization of the operational limits (i.e., sustained combustion limits) over a variety of fuel and air flow rates. Both advanced non-intrusive diagnostics (i.e. PLIF) and traditional methods were used to characterize the combustion and flowfield conditions.

## II.    Experimental Setup

### A.   Test Facility

The AFRL/PRAS Large-Scale Supersonic Combustion Research Facility is an in-house facility capable of allowing studies of the enhancement and control of fuel-air mixing in supersonic combustors with conventional and state-of-the-art non-intrusive diagnostic techniques.  The tunnel design provides optical access from up to three sides of the test section through fused silica windows which provide excellent transmissive properties in the ultraviolet wavelengths.  The nozzle sidewalls, as well as the top and bottom walls of the test section are equipped with conventional static pressure and thermocouple taps. Further details of the test facility are described elsewhere.[10]

A two-dimensional converging-diverging Mach 2 nozzle section, configured with an asymmetric nozzle, is used to develop the desired inlet conditions.  The facility nozzle is configured with nozzle blocks to create a 2-inch high by 6-inch wide exit to create the Mach 2 flow through the test section.  The test section is equipped with inserts to create a constant-area isolator section 7 inches in length.  The constant area isolator allows the tunnel to function in ramjet, scramjet and dual modes.  In the ramjet configuration, the backpressure is raised to move the shock structure completely into the isolator section creating purely subsonic flow in the test section.   Lowering the backpressure moves the shock structure into the test section.  Lowering the backpressure further creates purely supersonic flow in the test section.  The isolator section is followed by an insert creating an expansion section diverging at 2.5 degrees 29.125 inches in length.

### B.   Test Procedure

The cavity, shown in Figure 4, is recessed from the surface with a 90-degree rearward-facing step, and the trailing edge is configured with a 22.5-degree ramp.  The current flameholder configuration has a depth of 0.65 inches and a length of 2.60 inches. Fuel and air injection is accomplished through three sets of injection sites located along the aft ramp.  All injectors are directed parallel to the cavity floor.  Each spanwise row of injectors is fed from a single manifold and can be configured to inject either air or fuel.  This fueling scheme allows the fuel oxidizer to be obtained from main two sources: direct injection and free stream entrainment.  The upper (A2) and lower rows



Figure 4 – Cavity Hardware

(A1) of injectors were configured to inject air and consist of 11 orifices each with a diameter of 0.078 in.  The middle row (F1) was configured to inject ethylene and consists of 10 orifices each with a diameter of 0.063 inches. Injector centerlines were located 0.35, 0.55 and 0.75 inches vertically above the cavity floor.
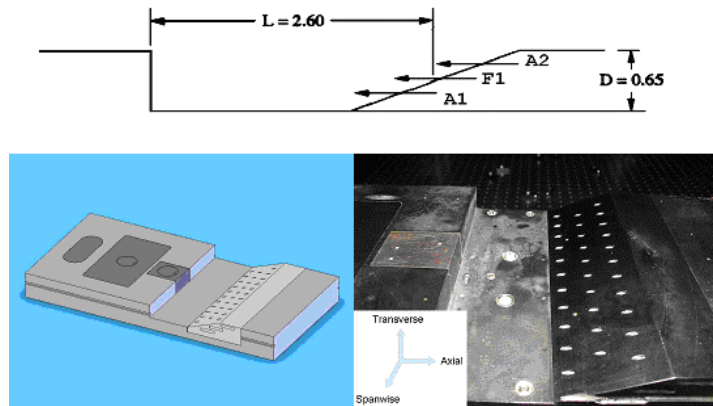
The fuel and air injection system was automated and interfaced with a computer based controller and data collection system.  The injection pressure was regulated with a dome loader and controlled remotely with an air-actuated isolation valve.   A pressure transducer and thermocouple were used to measure the pressure and temperature of the injectant.  Additional pressure and temperature data was gathered using a bank of Pressure Systems, Inc. strain gage transducers and Type-K thermocouples distributed about the test facility.  All data was recorded in a computer for future analysis.  The mass flow rate of gas was measured using a bank of Tylan mass flow controllers.  These mass flow controllers are manufactured to output air given their full scale rating which is measured in Standard Liters Per Minute (SLPM).  Because one of these controllers was configured to measure the flow rate of ethylene as opposed to air, a correction factor of 0.6 was applied in accordance with the Tylan mass flow controller users manual.  The ethylene fuel was introduced into the cavity using a 200 SLPM full scale mass flow controller and the air was metered by a 500 SLPM mass flow controller.

As with similar studies performed at this facility, the flow through the test section was stabilized at either a low or high backpressure condition.  Both conditions were established by manipulating a valve downstream of the test section.  Restricting flow increased the backpressure simulating the ignition transient at low Mach numbers.  On the other hand, opening the valve decreased the backpressure and simulated higher flight Mach numbers and supersonic flow through the combustor.   Only low backpressure cases were presented here because the associated flow dynamics present the greatest challenges for mixing and combustion.

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## C. Non-Intrusive Flow Diagnostics

OH-PLIF is used to track the presence of the hydroxyl radical produced during the combustion event within the cavity. For laser diagnostics using the OH-PLIF technique, a Lumonics Hyperdye dye laser is pumped with the second harmonic of an injection-seeded Spectra Physics neodymium doped yttrium-aluminum-garnet (Nd:YAG) laser (GCR-170). The dye laser output is frequency-doubled using an Inrad Autotraker III. For hydroxyl excitation, the dye laser was tuned to 587 nm so that the frequency-doubled radiation matched the wavelength for the $Q_1(8)$ transition of the $A^2\Sigma^+$-$X^2\Pi$ (1,0) band.

The laser sheet is formed using a pair of lenses, a plano-concave cylindrical lens (~150 mm focal length) and a plano-convex spherical lens (1000 mm focal length). This arrangement results in a sheet height of approximately 2 inches. The transmitting and receiving optical hardware are positioned on a transversing table allowing remote positioning of the measurement volume at any desired station in the flow field.

A Princeton Instruments PIMAX Charge-Coupled Device (CCD) digital camera with a 512 by 512 pixel array was used to detect the fluorescence. For OH LIF detection, fluorescence from the A-X(0,0) and (1,1) bands was isolated using UG-11 and WG-295 filters. The camera records non-time correlated images during the test condition. The camera is programmed to capture an image with each laser pulse. However, the frequency of the laser pulse is 100 Hz, faster than the refresh rate of the camera. The camera collects an image at the next laser pulse after refreshing, leading to the non-time correlation of the images. A benefit of this is the images avoid creating the impression of, or failing to detect, harmonic behaviors in the flow.

The profile or cross-flow visualization places the laser sheet on the center line of the test section. End view images are collected at stations 1, 2 and 3 located at 0.125, 1.5 and 2.5 inches aft of the forward cavity step respectively. Because of limited visual access through the end of the test section, the camera is place at an angle to the side window of the test section. Because the images were not corrected, distortion was evident.

A second optical high speed camera was placed perpendicular to the flow. This camera recorded light emitted within the visible spectrum at capture rates at approximately 3000 frames per second. The intensity of each pixel is the product of line integration across the span of the cavity. Areas of increased intensity were assumed to correlate to areas of increased combustion activity.

# III.    Results and Discussion

## A. PLIF Data Analysis

PLIF imaging is accomplished by exciting atoms and molecules using a two-dimensional area of laser light. The laser light energy is absorbed by the atoms and molecules which, in turn, can potentially decay back to the ground state. This release of energy is imaged at a right angle to the path of excitation onto a two-dimensional digital camera. As expected, the intensity of the image depends upon the chemical composition and local physical properties of the flow. This study will assume that increased image intensity is a function of increased concentration of OH. In other words, higher signal implies higher concentration.[8] Non-intrusive techniques namely PLIF and high speed digital emissions video was utilized to provide flow characterization data. The result of PLIF diagnostics was a series of approximately 100 iages and the product of the emissions diagnostics was recorded in *.avi format. These images were reduced primarily through the use of imaging software (Image J version 1.23 and PDView version 5.0) to determine the mean and standard deviation of a series of chronologically captured images. Mean images were use to characterize the intensity and concentration of hydroxyl radicals given high speed emissions camera and PLIF diagnostics respectively. Standard deviation results were considered to be a qualitative measure of unsteadiness and therefore flame instability.

The cavity was configured for air injection through the lower injection rows (A1) and for fuel injection through the center row (F1). The test conditions were nominally at Mach 2 with a stagnation pressure and temperature of 80 psia and 580°F with low backpressure (i.e. purely supersonic flow through the test section). Fuel was injected at 35%, 50% and 75% of full flow of the fuel mass controller (120 SLPM). This resulted in fuel flow rates of 38.4, 60 and 90 SLPM respectively. Baseline cases were run for all fuel flow cases (35%, 50% and 75%) and PLIF images were taken at all stations. The mean baseline results are shown in Figure 5. Stations 1 through 3 are labeled respectively and unless otherwise noted, all images are presented on the same intensity scale (1800-6000) to allow unbiased comparison. The scale presented above defines pixels with a value of 1800 to be represented by black and pixels with a value of 6000 to be represented as white. Pixels between 1800 and 6000 will be shown in shades of grey. The spanwise centerline of the cavity can be imagined as a vertical line located near the right-hand side of each image. Given that the images above were acquired at three different streamwise locations throughout the cavity, these images provide information as to where combustion was occurring within the cavity. An efficient cavity should exhibit evidence of combustion reactions, hydroxyl radicals (OH) in this case, throughout its volume.

The presence of OH is indicated by increased pixel intensity (white regions) within the photograph. This study will assume that the presence of OH is proportional to the combustion reaction rate that is taking place at the given section. However, it is important to note that the presence of OH at the measured location could be the result of the production at another location and subsequent diffusion and/or transport to the measured location. This is due to the relatively long life of the hydroxyl radical. Notice that the intensity is highest at stations 1 and 2 given the 32% fuel flow when compared to their respective stations at higher fuel flow rates. This is most notable for station 1 because based on this scale very little intensity is noted at station one for both increases in fuel flow above 32%. Furthermore, the overall intensity at stations 1 and 2 decreases with increases in fuel flow rate. This indicates that as fuel flow increases above 32%, combustion was negatively affected at streamwise stations forward of the aft ramp (stations 1 and 2).

Figure 5 – Baseline PLIF images

The baseline case exhibits the same trend observed in previous research. Specifically, a cavity that is directly fueled is optimally tuned for a single fuel flow rate. Increases or decreases from this "optimal" level lead to localized regions of combustion which can be interpreted as inefficient use of the cavity volume. From this standpoint, when fuel was injected at 38.4 SLPM (32%), the cavity was optimally tuned given the fuel only injection schemes studied and shown in Figure 5 because evidence of combustion was noted at all stations. Furthermore, the reader should note that the most significant change in image intensity as a function of fuel flow was noted at station 1 near the forward cavity step.

For the next study, air was directly injected through the bottom injection ports (A1) into the cavity to study its effects on combustion. This was accomplished using a mass flow controller with a full scale capability of 500 SLPM. The same fuel flow rates and injection locations were utilized for ease of comparison. Figure 6 shows the effects of air injection given a constant fuel flow rate of 32% (58.4 SLPM).

Figure 6 – 32% Fuel Flow

Air is injected at 50% (250 SLPM) in addition to the baseline (fuel only) case. Figure 6 shows an improvement in cavity combustion most notably at station 1 whereas very little change is noted at stations 2 and 3. This effect demonstrates that the direct injection of air through the bottom row of injectors can provide another mechanism to optimize the combustion process with the cavity. However as shown above, at this test point, increases in air injection do not necessarily result in improved combustion through the entire cavity because combustion at stations 2 and 3 remain largely unchanged. The most notable increase in combustion was at station 1 near the cavity step.

Similarly, fuel was introduced at 50% (60 SLPM) and air was injected at 50% (250 SLPM) and 75% (375 SLPM) in addition to the baseline (fuel only) case through A1. Figure 7 shows the effect of increased air flow
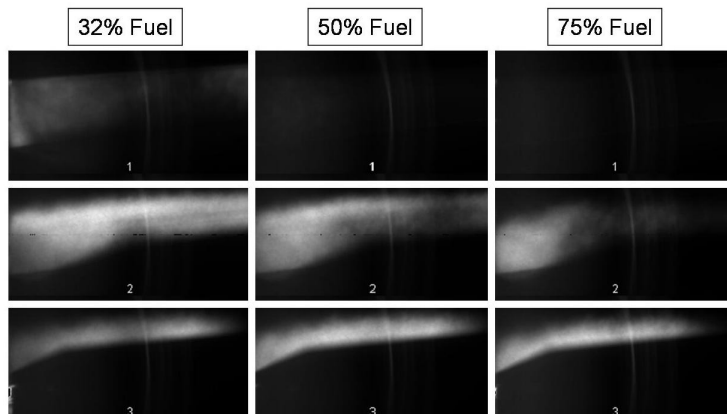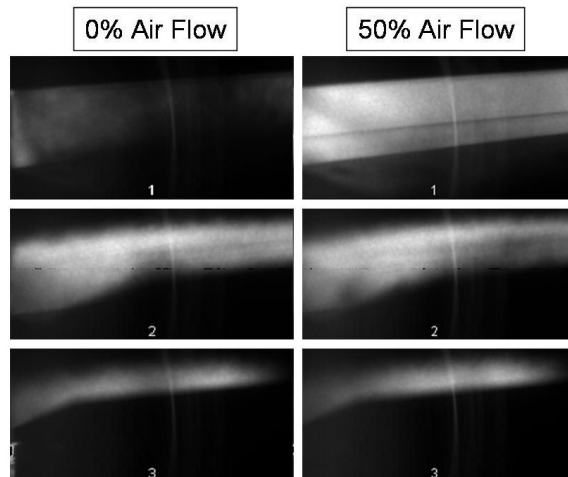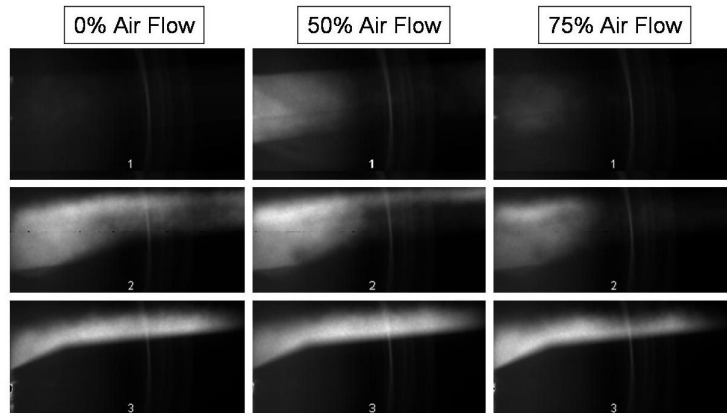
Figure 7 – 50% Fuel Flow

given a constant fuel flow rate of 50% (72 SLPM). The increase in airflow from the baseline case to 50% (250 SLPM) air injection flow rate caused an increase in combustion at station 1. However the continued increase in airflow from 50% to 75% (375 SLPM) resulted in a decrease in combustion at station 1. Image intensity remained steady for station 2 and 3 given all air loadings applied at this test point. Although there was insufficient resolution given the data to determine the airflow rate that provided the optimum utilization of cavity volume for this fuel loading, when the air flow was at 50%, station 1 exhibited the highest concentration of OH among conditions tested. In the same way that stations 2 and 3 were minimally affected by the introduction of air at 32% fuel loading, combustion at stations 2 and 3 at 50% fuel loading seem to be independent or weak functions of introduced air flow.



Figure 8 – 75% Fuel Flow

Fuel was introduced at 75% (90 SLPM) and air was injected at 85% (425 SLPM) through A1 in addition to the baseline (fuel only) case. Figure 8 shows the effect of increased air flow given a constant fuel flow rate of 75% (90 SLPM). The combination of this fuel loading and the introduction of air demonstrated similar trends compared to the 32% and 50% fuel flows. The greatest increase in intensity was evidenced at station 1 although stations 2 and 3 incurred a slight intensity increase given the increased air flow.

This fueling scheme, fuel injection at F1 and air injection at A1, produced an increase in combustion at station 1 in each of the three fuel flow rates. Figures 5 through 8 show that given direct air injection cavity combustion can be optimized for various fuel flow rates. However, as noted before, combustion is not necessarily improved uniformly throughout the cavity. The inconsistency in cavity combustion throughout the volume is a product of the complexities of mixing, variations in local temperature and pressure and three-dimensional cavity flowfields among a host of other parameters. Figures 1b and 1c show the stream traces of cavities with comparable geometry to the experimental hardware. Notice that two counter-rotating lobed structures are commonly found in such a configuration. This structure complicates the fuel and air transport mechanism especially near the cavity step. As noted before, mass (air, fuel and products of combustion) is transported at different rates between the freestream/cavity shear layer/aft vortex and the forward vortex/aft vortex. Previous aft ramp, direct fuel-only injection studies have concluded that for higher fuel flow rates a fuel rich region is formed near the cavity step.[4] This region, as implied, is not populated by a combustible mixture and therefore contributes to the overall inefficiency of the cavity volume.



A – Excess fuel is entrained by forward vortex and lacks sufficient oxidizer for combustion
B – Momentum of aft vortex and fuel injectant carry products of combustion and unburned fuel toward the cavity step
C – Combustion region

Figure 9 – Rich Cavity Combustion

The addition of air injection through A1 served to aid combustion at station 1 when compared to the baseline (fuel only) case. This observation was noted previously and evidence was presented in
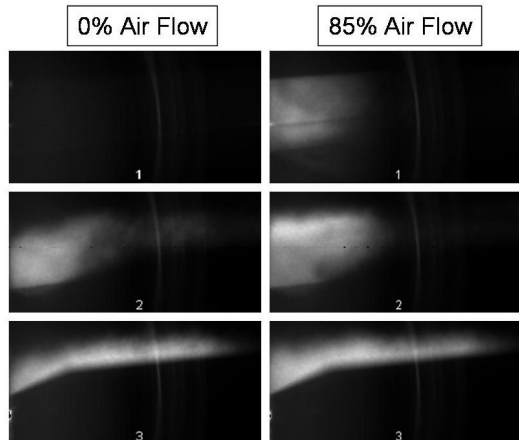


2000-8000 Mean

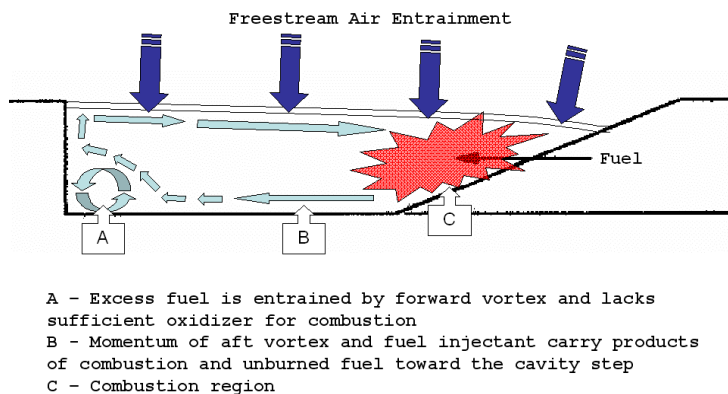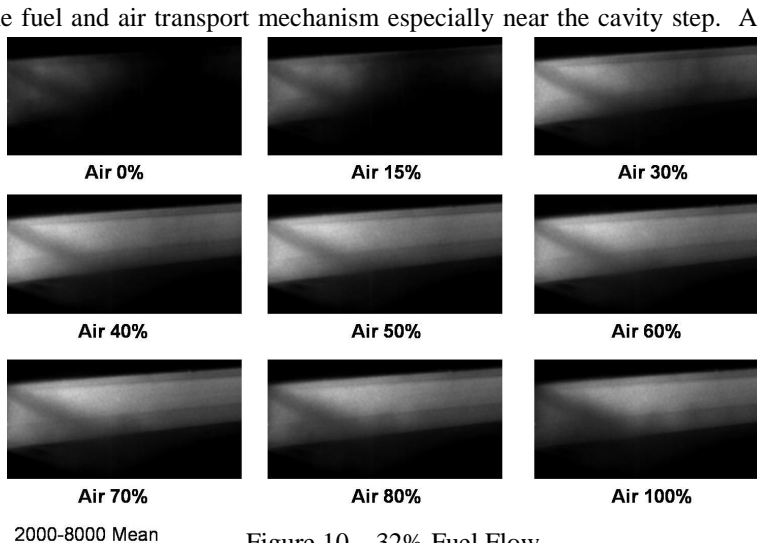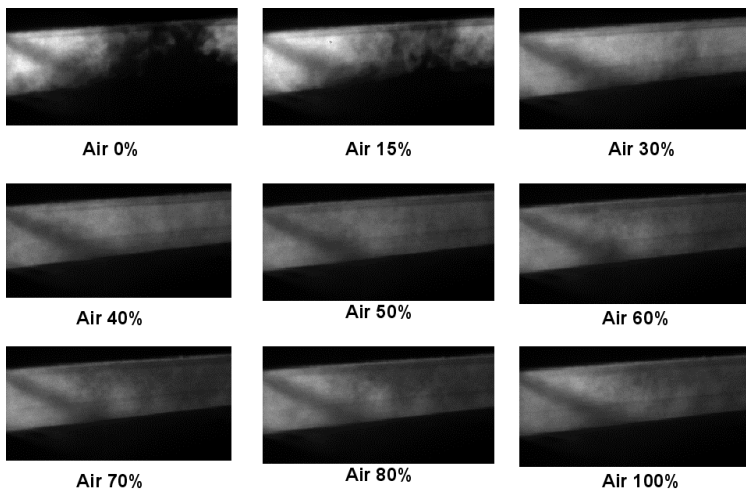Figure 10 – 32% Fuel Flow

figures 5 through 8.  As noted in Figure 9, the region sampled at 0.125 inches from the cavity step (station 1) has the potential to become "rich" in the absence of sufficient air injection given the fuel loading.  This tendency at station 1 to become rich is offset by the direct air injection.  Similar to the positive combination of fuel injectant and cavity vortex, air injected near the bottom cavity floor is complimentary to the local flowfield and improves air transport toward the cavity step.  However, this injection scheme merely provides another mechanism to optimize combustion over a range of operating conditions.  Increasing air injection without bound does not always equate to improved combustion.  Reference the images shown in the first row of Figure 7 corresponding to station 1.  Increasing the air flow from 50% to 75% at a fuel flow rate of 50% shows a decrease in combustion as inferred from OH concentration.

Air injection at the A1 site significantly altered combustion near the rear-facing step.  A follow-on investigation was initiated to further characterize the effects of air injection (A1) on combustion near the cavity step.  The chosen laser plane was located at 0.25 inches aft of the step, normal to the freestream direction and will be referred to as station 1a.  Several fuel flow rates were studied, however only the low fuel rate results are presented in this paper.  Optimum combustion at an arbitrary location is defined by steady, uniform combustion throughout the area.  Therefore, mean images with near constant high intensity and standard deviation images with constant low intensity should be representative of optimum combustion.  Figures 10 and 11 present the mean and standard deviation respectively of images taken at a fuel flow rate of 32% and various



Air 0%    Air 15%    Air 30%

Air 40%    Air 50%    Air 60%

Air 70%    Air 80%    Air 100%

10-1800 Standard Deviation    Figure 11 – 32% Fuel Flow

air injection mass flow rates.  The scale for each figure is included and takes the form of (black-white).  Figure 10 shows a gradual increase in the combustion present at station 1a given increases in air flow.  There is very little difference between the mean images acquired at an air flow of 40% through 90%.  Figure 11 is the standard deviation of all images collected at this test point.  The images from air injection between 30% and 90% are very similar for both the mean and standard deviations.  Stable combustion appears to be taking place at station 1a for air injection above 15% as indicated by the mean and standard deviation images.  For 32% fuel flow, 50% air flow seems to optimally tune the cavity evidenced by a relatively uniform bright mean and a relatively uniform dim standard deviation.

## B.  Luminous Flame Emissions

A high speed camera was positioned normal to the flow such that the entire cavity profile was visible.  This method provided an overall view of combustion as evidenced by the presence of luminous parts of the flame within the cavity and was used to further extend the combustion information extracted from the PLIF diagnostics.  No visible light emissions are shown in black while increases in flame emissions are reflected by increases in intensity (white).  Data was taken at three fuel flows, various air flows and both high and low backpressure.  A red reference line was added at the same location for each image.  This line was intended to define the cavity boundaries, however it must not be taken as an exact representation of the cavity.  Specific images within a table will be identified by the following: (row, column).



Air 0%    Air 15%    Air 30%

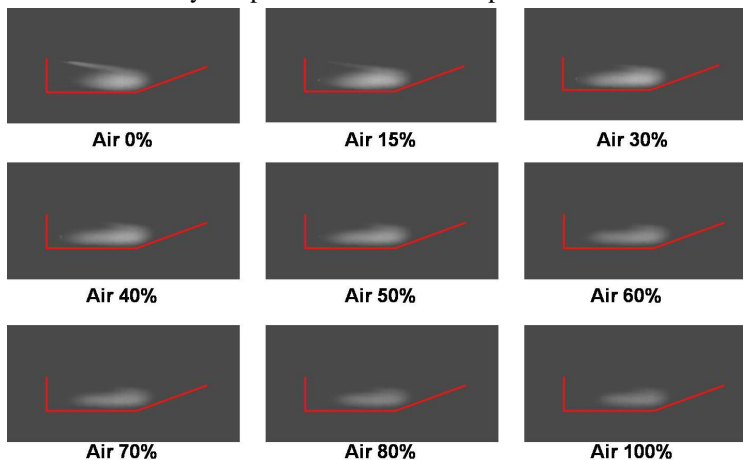Air 40%    Air 50%    Air 60%

Air 70%    Air 80%    Air 100%

Figure 12 – 32% Fuel Flow    Mean Images

The series of images shown in figure 12 were derived from the mean of all images acquired at 32% fuel flow, low backpressure and increasing air flow through A1. Increased air flow decreases mean combustion throughout the cavity. The presence of a strong shear layer flame that extends almost the entire length of the cavity is shown at 0% air injection. As air flow increases the shear layer flame draws into the aft ramp combustion region and is no longer clearly evident at 70% air flow. Furthermore, as air flow increases the combustion region decreases in streamwise length toward the aft ramp. The presence of a strong shear layer flame on the fuel only case (image (1,1)) is an indicator of near optimum cavity combustion. Since this occurs with no air injection, the addition of more air should tend to lean out the global cavity mixture further reducing overall cavity combustion.

The figure 13 was derived from the mean of all images acquired at 50% fuel flow, low back pressure and increasing air flow through A1. Increased air flow increases combustion throughout the cavity. Note that at 0% air flow combustion is localized near the aft ramp, but the existence of a shear layer flame is evident. As air flow is increased the shear layer flame extends farther from the aft ramp toward the forward step. Furthermore, at higher air loadings a non-reactive region is formed at the middle (streamwise) of the cavity.



Figure 13 – 50% Fuel Flow     Mean Images

Figure 14 shows the standard deviation images for 50% fuel flow, various air injection rates through A1 and low backpressure. It is obvious that the reference line does not exactly coincide with the cavity boundaries. However, it occupies a fixed location and served as a valid reference frame. All images, with the exception of (1,1) and (3,3), display a common attribute. They each exhibit a very consistent combustion region in the shear layer. This region is located by its low intensity. A strong shear layer flame is considered to be a good indicator of an effective flameholding mechanism. Such a mechanism serves to sustain combustion within the cavity through the production of hot byproducts of combustion. These hot products are re-circulated by the cavity vortex structure and provide thermal energy to promote combustion. Additionally, a shear layer flame is well suited to transfer energy in the form of heat to the freestream flow furthering combustion reactions outside of the cavity. Air injection through A1 continues to have a beneficial effect on cavity combustion. Given 50% fuel flow, combustion filled the entire cavity volume at nearly every air flow rate resulting in effective use of cavity geometry.
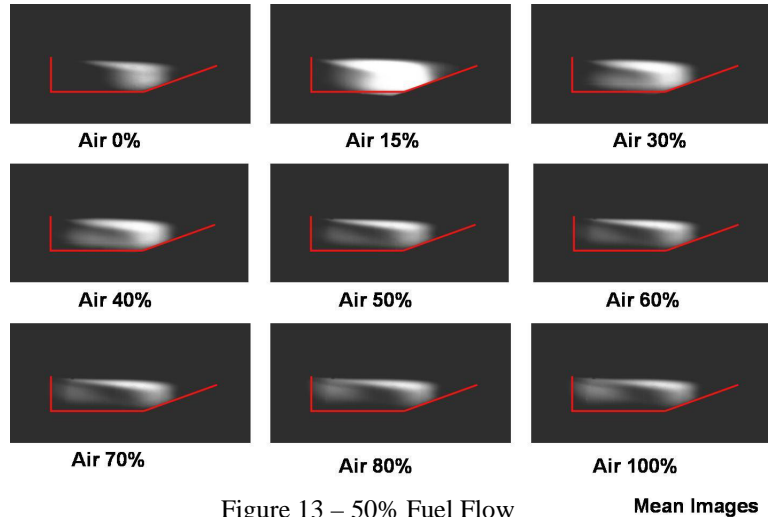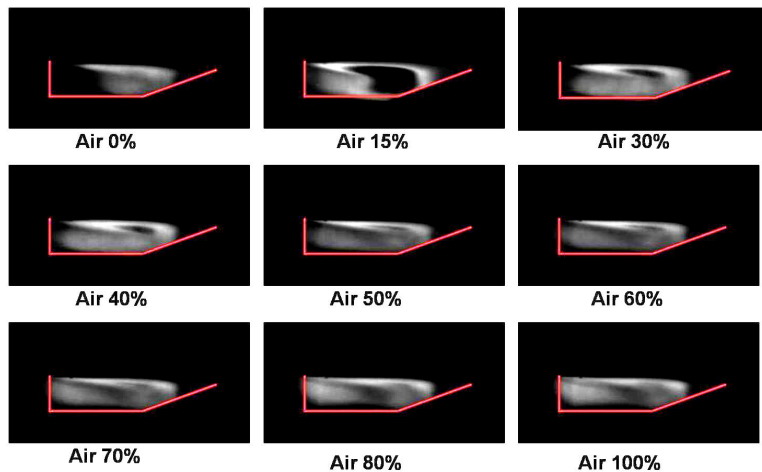


Figure 14 – 50% Fuel Flow     Standard Deviation Images

Figure 15 was derived from the mean of 200 images acquired at 75% fuel flow, low back pressure and increasing air flow through A1. Combustion at the fuel only case is localized near the aft cavity ramp. The sequential addition of air produced the following structures: formation of shear layer flame, extension of the shear layer flame from the aft ramp to the cavity step, and the addition of a combustion zone near the cavity step. The formation of these structures based on controllable parameters (i.e. fuel and air flow rates) allows the cavity to be tuned to best serve as a flameholder throughout various operating conditions.



Mean Images
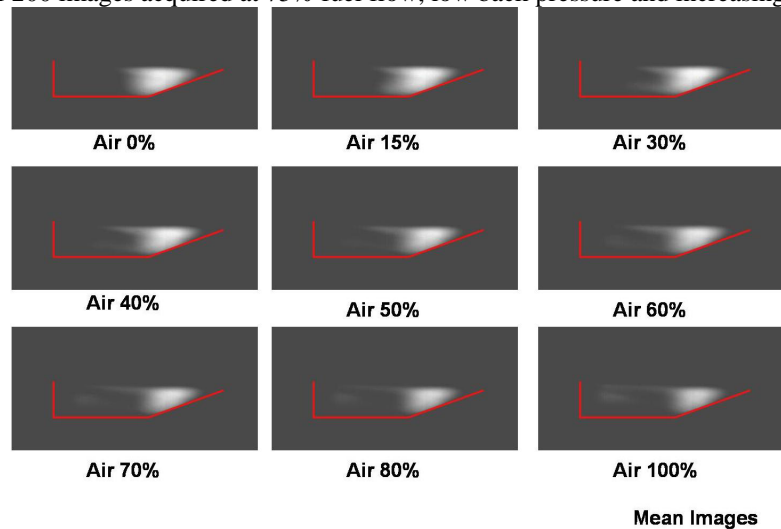
## IV.    Conclusions

Air injection from the bottom injection site (A1) served to tune the cavity for optimum combustion for each fuel flow rate. That is, for a given fuel flow rate, air injection flow rates can be increased or decreased to produce a stable, uniform combustion region throughout the cavity. Cavity aerodynamics have shown that more freestream air is entrained by the cavity given high backpressure. Previous fuel only studies have been limited to lower fuel flow rates especially at low backpressure, due to this limited air entrainment. Therefore, this fueling scheme, where air and fuel are directly injected into the cavity, significantly increases the operating limits of the cavity flameholder.

The addition of air injection serves to lean out fuel rich lobes shown to exist near the cavity step allowing for combustion throughout the cavity thereby increasing its efficiency. Injection at A1 produced the greatest region of impact near the cavity step. Without air injection, the cavity step region contributes very little to the overall cavity combustion. Air injection through the top spanwise row of injectors (A2) minimally affected global cavity combustion. However, a localized region of influence was visually noted.

Efficient combustion can be characterized by a strong, steady shear layer flame and global reaction, Increases in fuel flow, for the appropriate air flow, produced significant heat as evidenced by the increase in temperature within the cavity. The cavity step tended to retain the heat of combustion more so than the aft ramp, due to the cooling effects of the air and fuel flow through the ramp.

## Acknowledgments

## References

[1] Mercier, R., McClinton C., "Hypersonic Propulsion – Transforming the Future of Flight," AIAA paper 2003-2732, AIAA/ICAS International Air and Space Symposium and Exposition, Dayton, OH 14-17 July 2003

[2] Boudreau, A., "Status of US Air Force HyTech Program," AIAA paper 2003-6947, 12th AIAA International Space Planes and Hypersonic Systems and Technologies, Norfolk, VA 15-19 December 2003

[3] Youngbin, Yoon. "Blowout Stability Limits of a Hydrogen jet Flame In a Supersonic, Heated, Coflowing Air Stream." Combustion Science and Tecnology Vol 97 pp 137-156.

[4] Gruber, M.R., Donbar, J.M., Carter, C.D. and Hsu, K-Y., "Mixing and Combustion Studies Using Cavity-Based Flameholders in Supersonic Flow," *ISABE-2003-1204*

[5] Mathur, T., Billig, F., "Supersonic Combustion Experiments with a Cavity-Based Fuel Injector," *Journal of Propulsion and Power*, Vol. 17, No. 6, 2001, pp. 1305-1312.

[6] Gruber, M., Baurle,R., Mathur,T., and Hsu, K., "Fundamental Studies of Cavity-Based Flameholder Concepts for Supersonic Combustors", *Journal of Propulsion and Power*, Vol. 17, No. 1, 2001, pp. 146-153.

[7] Ben-Yakar, A., Hanson, R. K., "Cavity Flameholders For Ignition and Flame Stabilization in Scramjets: Review and Experimental Study," AIAA paper 98-3122, July 1998.

[8] Lee, M.P., McMillin, B.K., "Planar Fluorescence Imaging of a Transverse Jet in a Supersonic Crossflow," *Journal of Propulsion and Power*, Vol. 8, No. 4, 1992, pp. 729-735.[8] Hsu, K.-Y., Goss, L.P., and Roquemore, W.M., "Study on Trapped-Vortex Combustor-Effect of Injection on Flow Dynamics," *Journal of Propulsion and Power*, Vol. 14, No. 1, 1998, pp. 57-65.

[9] Gruber, M.R., Nejad, A.S., "Development of a Large-Scale Supersonic Combustion Research Facility," AIAA paper 94-0544, 32nd Aerospace Sciences Meeting and Exhibit, Reno, NV, 1994